

Research Paper

Spatiotemporal hydrochemical variations in river water in the Qilian Mountains and their sources: a case study of the Binggou River Basin

Junju Zhou, Juan Xiang, Guofeng Zhu, Li Lei, Jianjun Cao, Wei Shi, Wei Wei, Meihua Huang and Wei Feng

ABSTRACT

The headwater region of inland China is immensely important for sustaining livelihoods and maintaining ecological balance, highlighting the need to characterize and assess water quality in this region. The aim of this study is to acquire a comprehensive understanding of the spatiotemporal variation characteristics of river water chemistry and to identify the sources of major ions in the Binggou River Basin, Northwest China. The results show that the water of the Binggou River is neutral freshwater. SO_4^{2-} is the major anion, Ca^{2+} is the major cation and the river type is Ca–Na– SO_4 – HCO_3 . The concentrations of Na^+ , Mg^{2+} , SO_4^{2-} , NO_3^- , and total dissolved solid are slightly higher than the global average. The seasonal variations of major ion concentrations in the river are highest in winter but lowest in autumn, whereas the spatial variations are greater in the east branch than in the west branch and upstream compared with downstream. Source analysis of the ions indicates that rock weathering is the main source of ions, followed by human activities such as farmland fertilization and coal burning. Water quality analysis shows that the river water is suitable for drinking and irrigation, but the water quality is relatively poor in areas with more human activity, which indicates that human activity greatly influences water quality.

Key words | controlling factor, hydrogeochemistry, major ions, water quality

Junju Zhou
Juan Xiang (corresponding author)
Guofeng Zhu
Jianjun Cao
Wei Shi
Wei Wei
Meihua Huang
Wei Feng
College of Geography and Environmental Science,
Northwest Normal University,
Lanzhou 730070,
China
E-mail: xiagjuan@163.com

Guofeng Zhu
State Key Laboratory of Cryosphere Science,
Northwest Institute of Eco-Environment and
Resources,
Chinese Academy of Sciences,
Lanzhou 730000,
China

Li Lei
Management Bureau of Shiyang River Basin,
Gansu Provincial Water Resources Bureau,
Wuwei 733000,
China

INTRODUCTION

The chemical characteristics of river water reflect not only the water quality of the river but also the characteristics of and changes in the ecological environment of the river basin (Qiao *et al.* 2017; Ramesh *et al.* 2018). Studies of the chemical composition and distribution patterns in rivers can more fully reveal the sources of chemicals in the river water, the relationship between the river and the natural environment, and the influence of human activities on

the river (Pazi 2008; Tripathee *et al.* 2014). As global environmental problems intensify, scholars have increasingly focused on river chemistry problems (Connor *et al.* 2014; Nazri *et al.* 2016; Rodolfo *et al.* 2018). Research on river hydrochemistry first began in developed countries. Piper (1984) used trilinear charts to analyze the chemical composition of river water, and Gibbs (1970) studied the main sources of ions in rivers through the concentration

relationships between total dissolved solids (TDSs) and anions and cations. With the turn of the twenty-first century, academicians in developed countries began concentrating on the relationship between the ion content in the water of large catchments and regional geological lithology and climatic conditions, such as the Amazon basin (Mortatti & Probst 2003), the Mackenzie River of North America (Millot *et al.* 2003), and the Lena River Basin in Asia (Huh *et al.* 1998). The water chemistry characteristics of rivers can reflect water quality, and the analysis of river water quality based on water chemistry parameters is also a focus of water chemistry research (Aminiyan *et al.* 2016).

In China, studies of river water chemistry began in the early 1960s. Le & Wang (1963) analyzed the temporal and spatial variation in the chemical properties of rivers in China and provided a general picture of the chemical characteristics of rivers. Subsequent research on river water chemistry developed quickly in China. Studies of the ion chemical characteristics of river water in the Yangtze River, the Yellow River, and the Xiangjiang River found that ions are most obviously affected by rock weathering (Chen *et al.* 2006; Li *et al.* 2017). Some scholars have studied the concentration and characteristics of inorganic ions in different water bodies in the Hengduan Mountains based on the study of the hydrological relationships of different water bodies (Zhu *et al.* 2015). Related studies in the Qilian Mountains have mainly been concentrated in the western Qilian Mountains (Li *et al.* 2015; Liu *et al.* 2016). The characteristics of the temporal and spatial distributions of water chemistry and control factors have been studied extensively in inland river basins, including the Tarim River (Xiao *et al.* 2016), the Heihe River (Wen *et al.* 2004), and the Shiyang River (Yang *et al.* 2018). Although river chemistry research in China is relatively mature, further strengthening of the understanding of small watersheds in source areas of inland rivers is needed.

The basin of the Shiyang River, which is one of the three largest inland rivers in the Hexi Corridor of Gansu, is located in China between longitudes 102°22' and 104°16'E and latitudes 36°29' and 39°27'N (Shi *et al.* 2012). This basin belongs to the typical continental climatic zone, with little precipitation, strong evaporation, and drought (Zhou *et al.* 2012; Zhang 2015). The watershed system originates

from the southern Qilian Mountains, and melt-water and precipitation in mountain areas are the main sources of supply for the river. As the main river in the region, the Shiyang River supports not only the regional social and economic development and people's livelihoods but also the regional ecological security. However, due to the unreasonable utilization of water resources, ecological, social and economic problems have become increasingly serious, including the deterioration of water quality, reduced groundwater levels, land degradation, loss of biological resources, unsustainable economic development, and intergenerational conflict in water use (Ren 2017). Despite some achievements in recent years, the outlook remains grim. Consequently, better solutions to the water environmental problems in the Shiyang River Basin are urgently needed.

The Binggou River, which is located in the core water source area of the Shiyang River Basin, is one of the National First-grade Drinking Water Conservation Areas. Thus, this paper analyzes the chemical composition of the river water of the Binggou River Basin in the Qilian Mountains and the upper reaches of the Shiyang River using measured data. In addition, the spatial and temporal distribution and sources of different ions and water quality and the influence of human factors on the river are discussed. We anticipate that the findings from this study will help basin water resource managers optimize the management measures.

MATERIALS AND METHODS

Study area

The Binggou River is a tributary of the upper reaches of the Shiyang River in the Qilian Mountains. The elevation of the Binggou River Basin ranges from 1,928 to 4,736 m, and the height difference in the whole basin is 2,808 m (Figure 1). The annual average temperature, precipitation, and evaporation are 5 °C, 200–400 mm, and 1,300 mm, respectively, with a relatively dry climate. The rock type is mainly granite, and there are massive sulfide deposits of volcanic origin (Wang *et al.* 2011). The basin area is approximately 326 km². As the altitude increases, the main

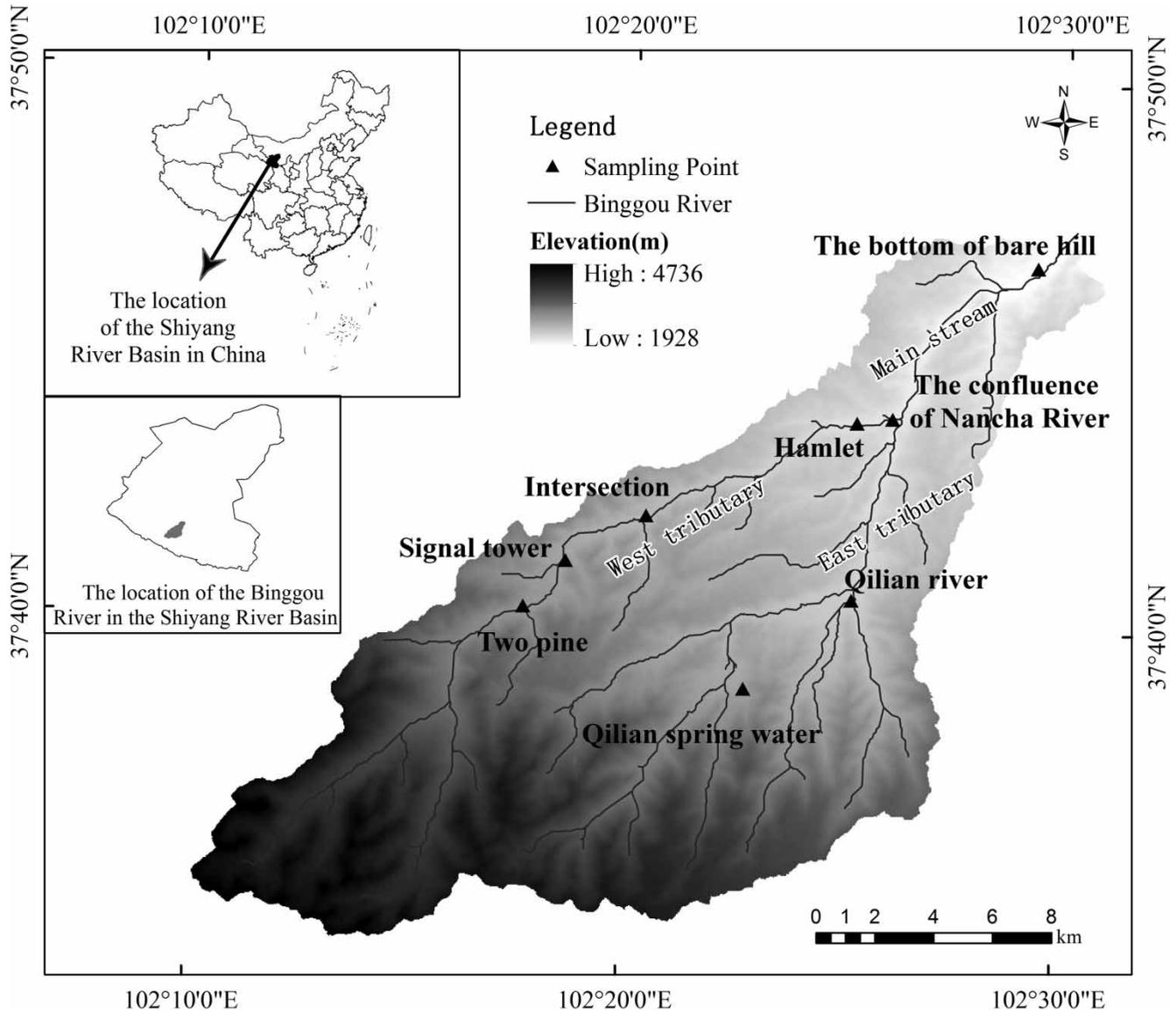


Figure 1 | Location of the Binggou River Basin and the sampling sites in this study.

land types are desert, grassland, woodland, alpine meadow, and permanent glacier.

The upstream area is mainly divided into two tributaries. Compared with the west branch, the east branch is shorter in mileage but broader with numerous small tributaries and a wide basin area. As a result, the west branch is sparsely populated, with only a small amount of farmland along the river banks and relatively few human activities. By contrast, along the east branch, there are many towns and villages and large areas of farmland along the riverside.

Sampling and analysis

In total, 72 water samples were collected from eight sampling sites (Table 1) in the river basin once a month between September 2016 and May 2017. Due to a road collapse, samples were not collected from June to August. The water samples were collected in clean 120-mL polyethylene bottles. Prior to sample collection, each sample bottle was washed with deionized water and then rinsed twice with the river water to be collected. After sample collection,

Table 1 | Longitude, latitude, and altitude of the sampling points

	Bottom of a bare hill	Confluence of Nancha River	Hamlet	Qilian River	Intersection	Signal tower	Qilian spring water	Two pines
Lon-E (°)	102.4891	102.4345	102.4208	102.4203	102.3404	102.3098	102.3795	102.2939
Lat-N (°)	37.7778	37.7309	37.7294	37.6756	37.6998	37.6855	37.6479	37.6713
Alt (m)	1,988	2,170	2,217	2,379	2,542	2,711	2,747	2,832

the bottle was immediately sealed, and a label with the corresponding time and place of the collection was attached. In addition, GPS was used to record the coordinates of the sampling points, and the geographical environment near the sampling point was recorded. All samples were frozen and transported to the State Key Laboratory of Cryospheric Science, Cold and Arid Regions Environment and Engineering Research Institute and Chinese Academy of Sciences for testing and analysis. Electrical conductivity (EC) and pH values were measured by an EC detector (LT-EC) and a pH instrument (PHS-3D), respectively. The pH meter was calibrated before each test, and the instrument was washed with distilled water before measuring each sample. TDSs and salinity (SAL) were tested by HANNA (HI3512). Before testing ion content, all samples were filtered using 0.45- μm polycarbonate microfiber filters. Major cations (Na^+ , K^+ , Mg^{2+} , and Ca^{2+}) were analyzed by a Dionex-600 ion chromatograph, and major anions (Cl^- , SO_4^{2-} , and NO_3^-) were analyzed by a Dionex-3000 ion chromatograph. Bicarbonates were determined according to the charge balance as described by Trower (2009). Comparison testing showed that the contamination of the samples during sampling, transportation, and treatment could be ignored.

Land use and cover data were acquired by a visual interpretation combining a long-term field survey with remote sensing images such as Landsat 8, Sentinel, and Google. The accuracy of the interpretation was 92.5%. The track number of the TM image data was 132–33, and the time of image generation was 10 August 2016. The geometric correction was carried out based on control points collected from the map at a scale of 1:10,000,000, and the position error was within 2 pixels. Based on the spectral information and texture characteristics of the remote sensing images in combination with the characteristics of the study area, the land use and cover in the study area were

divided into eight types. Temperature and precipitation data were grid data from the same period obtained from the China Meteorological Data Service Center (CMDSC). Runoff data were acquired from the Management Bureau of Shiyang River Basin. Evaporation data were calculated using the Penman–Monteith model and the H formula.

Mathematical and statistical analyses of the meteorological and water chemistry data were performed in the software SPSS 21, and the results of the analyses were plotted using the software Origin 8.0. The analysis, processing and mapping of the land use data were performed on the ArcGIS 10.2 platform. The Piper diagram method for water chemistry data was implemented in the software GW-chart.

RESULTS

General hydrogeochemistry

As shown by the results of the sample analysis in Table 2, the average pH of the river water is 7.83, indicating neutral water, with slight variations among the different sampling sites. SAL ranges from 0.06 to 0.15 (ppt), and the average value is 0.1 (ppt). The average EC is 208.45 ($\mu\text{S}/\text{cm}$), with a range of 132.71–318.00 ($\mu\text{S}/\text{cm}$). The differences in EC and TDS values among the different sampling points are obvious, with corresponding ranges of 185.29 ($\mu\text{S}/\text{cm}$) and 125.42 (mg/L), respectively.

The average concentrations (mg/L) of the major cations exhibit the following pattern of dominance: $\text{Ca}^{2+} > \text{Na}^+ > \text{Mg}^{2+} > \text{K}^+$. The dominant cation in the Binggou River is Ca^{2+} , accounting for 44%, followed by Na^+ and Mg^{2+} at 36% and 18%, respectively. The average contents of the main anions decrease in the following order: $\text{SO}_4^{2-} > \text{HCO}_3^- > \text{NO}_3^- > \text{Cl}^-$. The dominant anion is SO_4^{2-} ,

Table 2 | Physical and chemical parameters of the water samples from the Binggou River

	EC ($\mu\text{S}/\text{cm}$)	TDS (mg/L)	SAL (ppt)	pH	Na ⁺ (mg/L)	K ⁺ (mg/L)	Mg ²⁺ (mg/L)	Ca ²⁺ (mg/L)	Cl ⁻ (mg/L)	SO ₄ ²⁻ (mg/L)	NO ₃ ⁻ (mg/L)	HCO ₃ ⁻ (mg/L)
Bottom of a bare hill	197.68	131.41	0.11	7.76	10.45	0.58	3.71	12.84	3.46	13.40	2.12	11.76
Confluence of the Nancha River	201.67	134.33	0.10	7.78	5.55	0.26	3.31	13.85	1.78	15.70	2.02	5.27
Hamlet	191.81	127.20	0.09	7.67	6.49	0.29	3.55	14.80	2.00	16.30	2.34	6.66
Qilian River	264.00	176.00	0.13	8.00	15.75	0.67	8.53	9.69	5.99	19.90	6.55	2.41
Intersection	182.73	121.24	0.09	7.75	4.57	0.28	3.30	13.42	1.35	13.25	2.29	8.14
Signal tower	178.97	118.89	0.09	7.82	4.56	0.33	2.84	11.41	1.72	14.28	2.13	6.50
Qilian spring water	318.00	213.00	0.15	8.04	24.83	0.93	10.40	9.83	7.14	23.39	8.22	4.06
Two pines	132.71	87.58	0.06	7.86	5.03	0.46	1.71	8.90	2.04	5.93	1.49	11.50
Mean	208.45	138.71	0.10	7.83	9.65	0.48	4.67	11.84	3.19	15.27	3.40	7.04
Minimum	132.71	87.58	0.06	7.67	4.56	0.26	1.71	8.90	1.35	5.93	1.49	2.41
Maximum	318.00	213.00	0.15	8.04	24.83	0.93	10.40	14.80	7.14	23.39	8.22	11.76
Range	185.29	125.42	0.09	0.37	20.27	0.67	8.69	5.90	5.79	17.46	6.73	9.35
Variation coefficient	0.27	0.28	0.27	0.02	0.75	0.50	0.66	0.19	0.69	0.34	0.74	0.47
Global mean	–	120	–	8	6.30	2.30	4.10	15	7.80	11.20	1	58.40
WHO limit	–	1,000	–	6–8.50	200	100	50	100	250	250	50	600

accounting for 53%, followed by HCO₃⁻ at 24%. The chemical type of the river water in this area is Ca–Na–SO₄–HCO₃. The variation coefficients of Na⁺, Mg²⁺, Cl⁻, and NO₃⁻ are highest, with values of 0.75, 0.66, 0.69, and 0.74, respectively, while the variation coefficients of Ca²⁺ and SO₄²⁻ are lower, 0.19 and 0.34. In addition, the contents of Na⁺, Mg²⁺, SO₄²⁻, NO₃⁻, and TDS are slightly higher than the global averages for rivers (Meybeck 2003).

Seasonal variations of hydrogeochemistry

The physical and chemical parameters of the river water in different seasons are shown in Figure 2. Compared to spring, the contents of TDS and EC are higher in winter and lower in autumn. The pH, SAL, and Mg²⁺ are relatively stable among the three seasons. The concentrations of Ca²⁺ and HCO₃⁻ are highest in spring, whereas the concentrations of the other major ions are highest in winter, with obvious seasonal variations of Cl⁻, NO₃⁻, Na⁺, Ca²⁺, and HCO₃⁻ in the three seasons. As shown in the Piper diagram (Figure 3(a)), the variations in the anions are greater than those of the cations, with the largest change in the content of SO₄²⁻. The changes in the cations are less

obvious, except that the value of Ca²⁺ is lowest in winter, whereas the other cations are highest in winter. In all three seasons, the concentrations of the cations in the river decrease in the following order: Ca²⁺ > Na⁺ > Mg²⁺ > K⁺. The concentrations of the anions vary in the different seasons and exhibit the order SO₄²⁻ > HCO₃⁻ > Cl⁻ > NO₃⁻ in spring and winter and SO₄²⁻ > HCO₃⁻ > NO₃⁻ > Cl⁻ in autumn. The type of hydrochemistry is SO₄–Ca in all three seasons.

Spatial variations

The spatial variations in the concentrations of major ions in the Binggou River are shown in Figure 4. The values of SAL and pH are stable among all sampling sites. Other major ions and physical parameters are abnormal in the Qilian River and Qilian spring water sampling points, including extremely low Ca²⁺ and HCO₃⁻ concentrations and very high concentrations of the other ions, particularly SO₄²⁻, Mg²⁺, and Na⁺. The average values of EC, TDS, SAL, and pH are much higher in the east branch than in the west branch upstream and the main stream, with the values of 291 (mg/L), 194.5 (mg/L), 0.14 (ppt), and 8.02, respectively. The concentrations of Ca²⁺ and

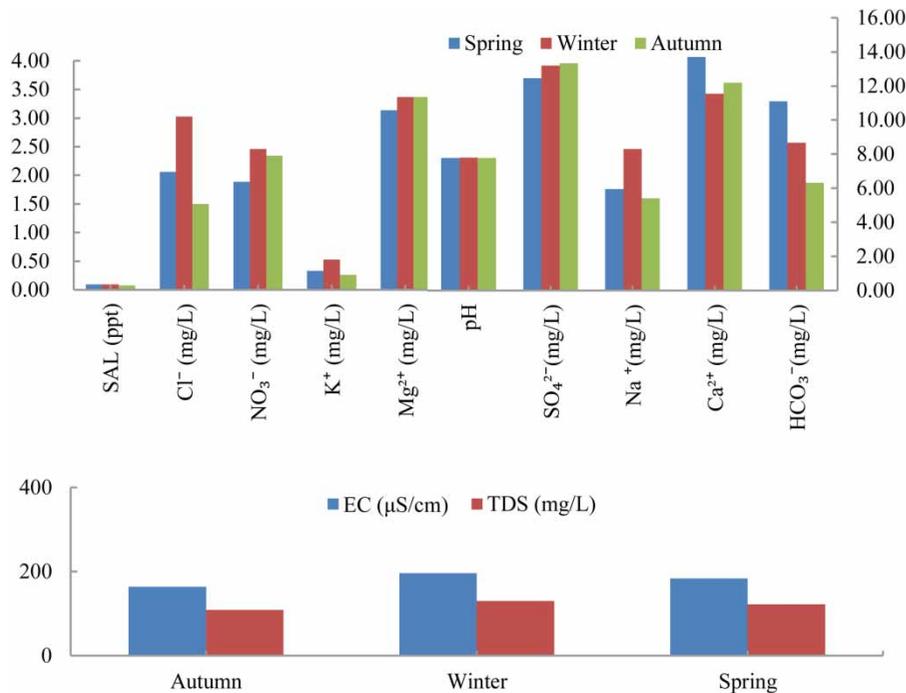


Figure 2 | Seasonal variation in the average content of major ions in the Binggou River.

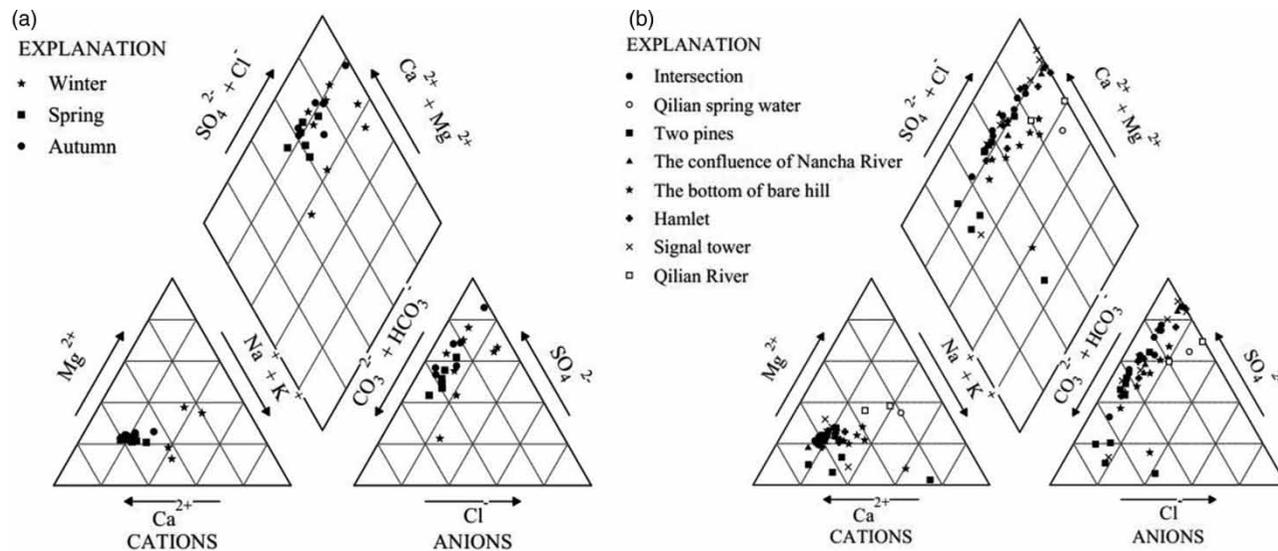


Figure 3 | Piper diagram of the major ion chemistries in different seasons (a) and different sampling sites (b).

HCO_3^- are lower in the east branch than in the west branch upstream and the main stream, but all other major ions are higher in the east branch, among which SO_4^{2-} , Na^+ , NO_3^- , Cl^- , and Mg^{2+} account for 44.5%, 60.67%, 64.1%, 59.9%, and 59.8% of the whole basin, respectively. The contents of EC,

TDS, SAL, and other major ions are higher in the west branch than in the main stream, but the pH is the same as that in the main stream (7.77) (Table 3). The hydrochemical type of the east branch is $\text{SO}_4\text{-Na}$, and the hydrochemical types of the west branch and main stream are both $\text{SO}_4\text{-Ca}$ (Figure 3).

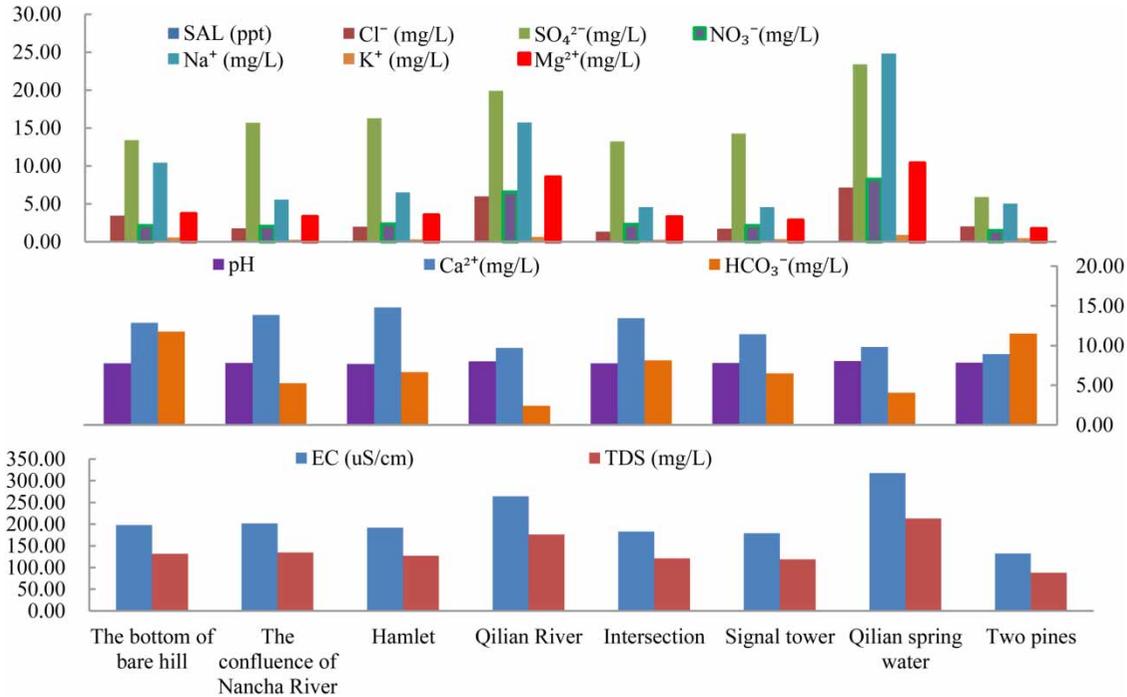


Figure 4 | Spatial variations of the concentrations of major ions in the Binggou River.

Table 3 | Average values of various ions upstream and downstream

	EC ($\mu\text{S}/\text{cm}$)	TDS (mg/L)	SAL (ppt)	pH	Cl ⁻ (mg/L)	SO ₄ ²⁻ (mg/L)	NO ₃ ⁻ (mg/L)	Na ⁺ (mg/L)	K ⁺ (mg/L)	Mg ²⁺ (mg/L)	Ca ²⁺ (mg/L)	HCO ₃ ⁻ (mg/L)
East branch	291.00	194.50	0.14	8.02	6.56	21.64	7.39	20.29	0.80	9.47	9.76	3.24
West branch	199.67	132.87	0.10	7.77	2.62	14.55	2.07	8.00	0.42	3.51	13.35	8.52
Main stream	171.56	113.73	0.08	7.77	1.78	12.44	2.06	5.16	0.34	2.85	12.13	8.20

Associations among the hydrogeochemical attributes

The correlation analysis of the ions in the Binggou River Basin is presented in Table 4. There are significant correlations ($p < 0.01$, $R^2 = 0.935$) between Cl⁻ and Na⁺ in the river water, indicating that these two ions have the same source. However, the concentration ratio of the two ions (Na⁺/Cl⁻) is 3.03, suggesting substantial redundant Na⁺. Na⁺ is also highly correlated with NO₃⁻ and Mg²⁺ at the test level of $p < 0.01$, with R^2 values of 0.819 and 0.813, respectively. These results indicate that the weathering of magnesium carbonate rock contributes greatly as an ion source in the river. NO₃⁻ shows a strong positive correlation with Mg²⁺ at the test level of $p < 0.01$

($R^2 = 0.966$). In addition, there is a slight correlation between HCO₃⁻ and Ca²⁺ at the test level of $p < 0.05$ ($R^2 = 0.509$). In this study, the concentration ratio of the two ions (Ca²⁺/HCO₃⁻) is 1.68, suggesting a contribution of sources other than rock weathering to Ca²⁺ and HCO₃⁻.

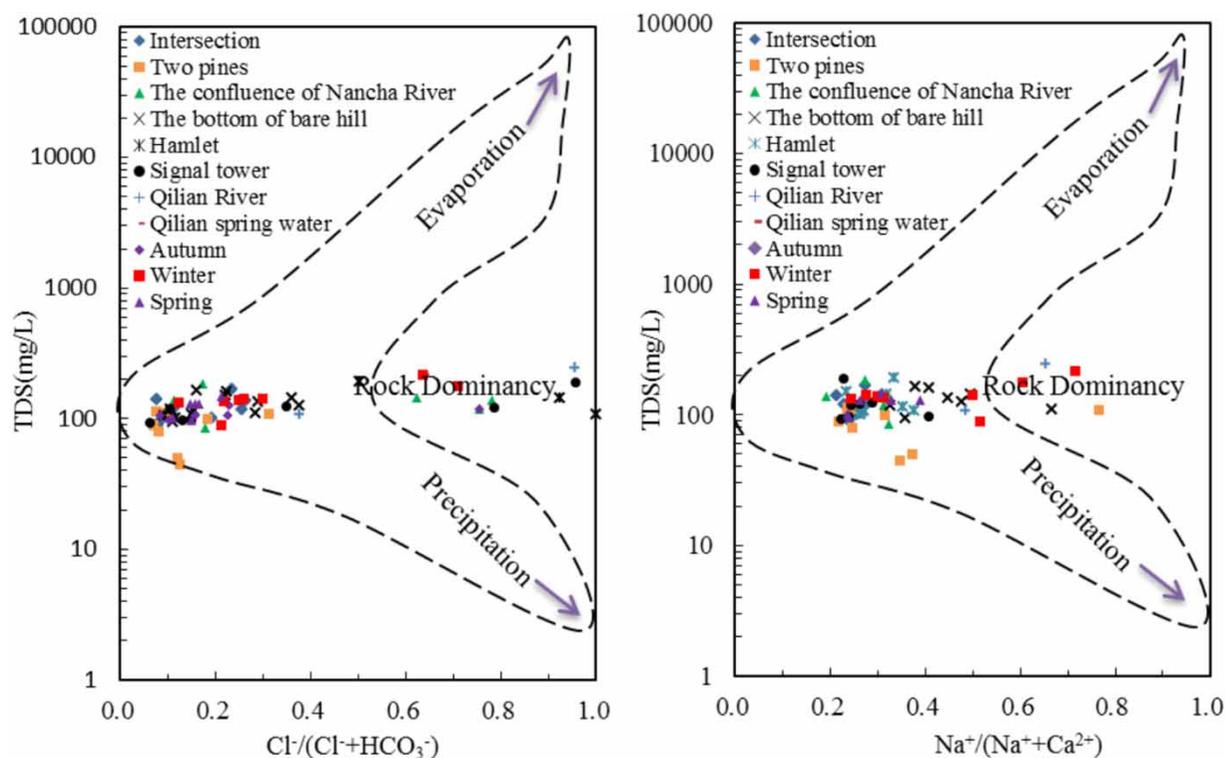
DISCUSSION

Rock weathering

As shown in the Gibbs diagram (Figure 5), the sampling points are mainly concentrated on the left side of the

Table 4 | Correlation analysis of major ions in the Binggou River

	Na ⁺	K ⁺	Mg ²⁺	Ca ²⁺	Cl ⁻	SO ₄ ²⁻	NO ₃ ⁻	HCO ₃ ⁻
Na ⁺	1	0.571*	0.813**	-0.970**	0.935**	-0.225	0.819**	-0.544*
K ⁺		1	0.131	-0.649**	0.703**	-0.842**	0.282	0.31
Mg ²⁺			1	-0.823**	0.757**	0.259	0.966**	-0.871**
Ca ²⁺				1	-0.965**	0.251	-0.869**	0.509*
Cl ⁻					1	-0.33	0.796**	-0.43
SO ₄ ²⁻						1	0.12	-0.676**
NO ₃ ⁻							1	-0.764**
HCO ₃ ⁻								1

p* < 0.05, *p* < 0.01.**Figure 5** | Gibbs diagram of the spatiotemporal variations of the ratios of Cl⁻/(Cl⁻ + HCO₃⁻) and Na⁺/(Na⁺ + Ca²⁺) as a function of TDS.

graph, with a small number of points distributed to the right and beyond the range of the dotted lines. This distribution shows that rock weathering is the main source of ions in the river water, whereas evaporation and precipitation have limited influence. Granite is the main rock in the basin, primarily in the form of O-Type adakite (sodium-

rich), which is the main source of Na⁺, Mg²⁺, and K⁺. The shale and conglomerates distributed in the basin are mainly carbonate rocks such as calcareous shale and limestone, which are the main sources of Ca²⁺ and HCO₃⁻. In addition, the massive sulfide deposits distributed in the basin are among the sources of SO₄²⁻ (Wang *et al.* 2011).

Effects of different sources of river water on ion concentrations

In this inland area of Northwest China, the monsoon season lags slightly, and precipitation is the main source of the supply of river water in autumn. In winter, there is very little precipitation, and the temperature is low; consequently, the groundwater supply is the main source of river water. In the spring, as the temperature rises, melt-water becomes the main source of supply, along with a small amount of precipitation (Figure 6).

The seasonal variations of the ion concentrations in the river showed that, among the three seasons, the concentrations of Cl^- , K^+ , Na^+ , and Mg^{2+} are highest in winter. In winter, groundwater is the major source of river water, and thus, the ions in the river water are mainly carried by groundwater. Granite and sulfide deposits are widely distributed in this area, and the long-term erosion of rocks underground is the main factor affecting ion concentrations in the river. The concentrations of Ca^{2+} and HCO_3^- are highest in spring. In spring, the water is mainly composed of melt-water, and surface erosion by this abundant melt-water is obvious. As carbonate rocks are distributed on the surface, the weathering and erosion of these surface carbonate rocks are the main sources of Ca^{2+} and HCO_3^- . The concentrations of NO_3^- and SO_4^{2-} are highest in autumn when the concentrations of other ions are generally lower. The effects of falling dust and infiltration of farmland are obvious in autumn, indicating that farmland and the atmosphere are important sources of NO_3^- and SO_4^{2-} .

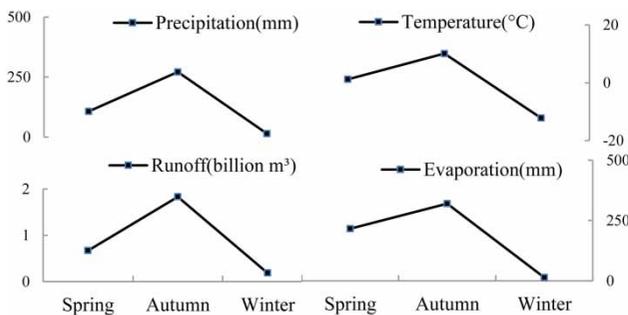


Figure 6 | Seasonal differences in major meteorological elements and runoff in the Binggou River Basin.

Influence of human activities on river water ions

In the upper reaches of the basin, there is little difference in land cover and use types between the east and west branches, but there are significant differences in the distribution of farmland and construction land (Figure 7). As shown in Table 5, the farmland area of the east branch accounts for 75% of the total area of farmland in the whole river basin. Construction land accounts for 57% of the total construction land in the basin. These values clearly indicate that human activities are altering the underlying surface in this area. By contrast, the west branch and the main stream are less affected by human activities. People are mainly engaged in seedling cultivation, planting of Ginseng fruit, highland barley, and Chinese yam and other agricultural activities in which nitrogen fertilizer and farmyard manure are important components of the crop planting process. In addition, coal is the main fuel. These materials are important sources of SO_4^{2-} , NO_3^- , and Na^+ in the river water of the east branch.

Compare with other alpine regions

Studies of rivers in other alpine regions of China have found similar results, including weakly alkaline river water, Ca^{2+} and HCO_3^- as the major ions, obvious spatial and temporal differences in ion concentrations, and rock weathering as the main source of ions in rivers (Pu et al. 2012; Feng et al. 2014; Wu et al. 2017). However, there are some differences: the river water chemical characteristics of the Yulong Mountains are also affected by monsoons (Pu et al. 2012) and the rivers in the Tianshan Mountains are affected by evaporation and have relatively high SO_4^{2-} concentrations (Feng et al. 2014).

The rock weathering is the major ion source in the Binggou River Basin, which is consistent with other regions, but SO_4^{2-} is the major anion in the study area, while the concentration of HCO_3^- is relatively low. Because the study area is located at the intersection of the monsoon zone and non-monsoon zone, the climatic conditions are complex. Moreover, the geological conditions of the Qilian Mountains are unique, with differences in rock types compared with other regions and more frequent human activities. Therefore, further studies are necessary.

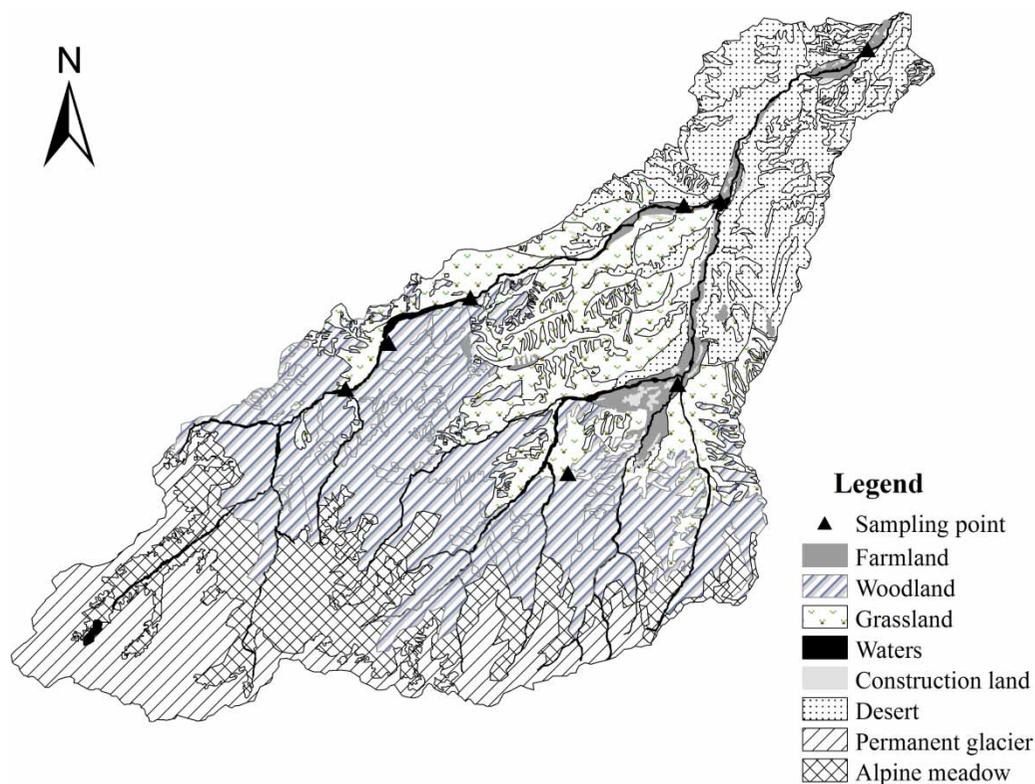


Figure 7 | Distribution of land use and cover types in the Binggou River Basin.

Table 5 | Spatial distribution of farmland and construction land in the Binggou River Basin

	East branch	West branch	Main stream	Total
Construction land (acres)	955	267	458	1,680
Farmland (acres)	8,496	1,455	1,418	11,369

Suitability of river water for drinking and irrigation

The drinking water quality standard issued by the World Health Organization (WHO) is adopted in this paper (Table 2; WHO 2011). The results show that the quality of the river water is far below the upper limit of the standard range, indicating that the river water is very suitable for drinking. However, Na^+ , Mg^{2+} , SO_4^{2-} , NO_3^- , and TDS levels are all slightly higher than the global average for rivers (Meybeck 2003), which indicate that the suitability of river water for drinking is slightly worse than the world average. In addition, the water quality is closer to the upper limit of the drinking water standard in the east

branch than in the other areas (Table 3), mainly due to the obvious human activities in the east branch.

The concentration of Na^+ is an important index for evaluating the suitability of water for irrigation. High sodium content may lead to the replacement Ca^{2+} and Mg^{2+} by Na^+ , and the displacement of Ca^{2+} and Mg^{2+} may reduce soil permeability, thus affecting crop growth. Therefore, the suitability of river water for irrigation can be assessed by $\text{Na}^+\%$ and the sodium adsorption ratio (SAR) (Ramesh *et al.* 2018):

$$\text{Na}^+\% = [(\text{Na}^+ + \text{K}^+)/(\text{Ca}^{2+} + \text{Na}^+ + \text{Mg}^{2+} + \text{K}^+)] * 100 \quad (1)$$

$$\text{SAR} = \text{Na}^+ / \sqrt{(\text{Ca}^{2+} + \text{Mg}^{2+})/2} \quad (2)$$

As shown in Figure 8, the $\text{Na}^+\%$ values of the Qilian spring and Qilian River sampling points on the east branch are within the range of 40–60 in the monitoring period, whereas the values in the other regions are less than 40. Although these results show that the water of the Binggou River meets the requirements for irrigation, the east branch

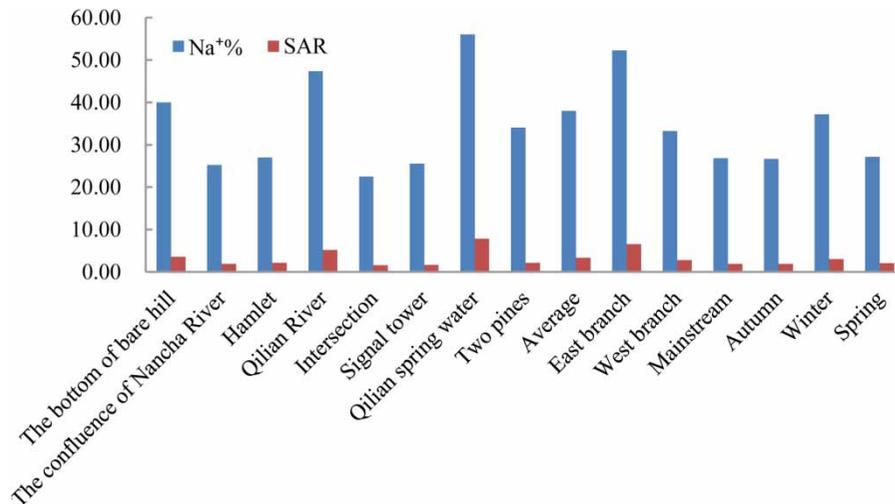


Figure 8 | Spatiotemporal variations of Na⁺% and SAR.

of the river is approaching the critical value of 60 (Wilcox 1948). Thus, the formulation of countermeasures is urgently needed to prevent further worsening of water quality. The lower the SAR value of a river, the more suitable it is for irrigation. When the SAR value is over 18, the water quality of the river does not meet the requirements for irrigation (Saleh *et al.* 1999). The SAR value of the Binggou River is less than 10, but the value of the east branch is obviously higher, which is consistent with the results of Na⁺%.

CONCLUSION

The results revealed that most of the hydrochemical attributes of the Binggou River Basin show obvious spatiotemporal variations due to the distinct lithology, the seasonal differences in precipitation in the inland arid climate, and the complex interactions with anthropogenic components. The variations of major ion concentrations in the river water are higher during winter but lower in summer and higher in the upstream east branch than in the upstream west branch and, in turn, the main stream. The analysis showed that rock weathering is the main source of ions in the river water, followed by human activities such as farmland fertilization and coal burning. The water quality fully meets the standards for drinking and irrigation, but the regional differences are large, and human activities have a certain impact on river water quality.

ACKNOWLEDGEMENTS

This research was financially supported by the National Natural Science Foundation of China (41761047, 41661005, and 41261104), the National Natural Science Foundation Innovation Research Group Science Foundation of China (41421061), and the Autonomous Project of State Key Laboratory of Cryosphere Sciences (SKLCS-ZZ-2017).

REFERENCES

- Aminiyan, M. M., Aminiyan, F. M. & Heydariyan, A. 2016 Study on hydrochemical characterization and annual changes of surface water quality for agricultural and drinking purposes in semi-arid area. *Sustainable Water Resources Management* **2** (4), 473–487.
- Chen, J. S., Wang, F. Y. & Xia, X. H. 2006 Geochemistry of water quality of the Yangtze River Basin. *Earth Science Frontiers* **13** (1), 74–85.
- Connor, N. P., Sarraino, S., Frantz, D. E., Bushaw-Newton, K. & MacAvoy, S. E. 2014 Geochemical characteristics of an urban river: influences of an anthropogenic landscape. *Applied Geochemistry* **47** (8), 209–216.
- Feng, F., Feng, Q., Li, Z. Q., Liu, W. & Jin, S. 2014 Analysis on the hydrochemical characteristics in the Upper Reaches of Urumqi River Basin, Eastern Tianshan. *Journal of Nature Resources* **29** (1), 143–155.
- Gibbs, R. J. 1970 Mechanisms controlling world water chemistry. *Science* **3962** (170), 1088–1090.
- Huh, Y., Tsoi, M. Y., Zaitsev, A. & Edmond, J. M. 1998 The fluvial geochemistry of the rivers of Eastern Siberia: I. Tributaries of the

- Lena River draining the sedimentary platform of the Siberian Craton. *Geochimica et Cosmochimica Acta* **62** (10), 1675–1676.
- Le, J. X. & Wang, C. D. 1963 Chemical characteristics of river water in China. *Acta Geographical Sinica* **29** (1), 1–13.
- Li, Z. X., Qi, F., Li, J. G., Pan, Y. H., Wang, T. T., Liu, L., Guo, X. Y., Gao, Y., Jia, B. & Guo, R. 2015 Environmental significance and hydrochemical processes at a cold alpine basin in the Qilian Mountains. *Environmental Earth Sciences* **73** (8), 4043–4052.
- Li, C. Q., Wang, P. & Li, Y. 2017 Temporal-spatial characteristics of water chemistry and influencing factors in the Ganjiang River. *Environmental Chemistry* **36** (9), 1949–1956.
- Liu, W., Li, Z. J. & Song, L. L. 2016 The evolution of hydrochemistry at a cold alpine basin in the Qilian Mountains. *Arabian Journal of Geosciences* **9** (4), 301.
- Meybeck, M. 2003 Global occurrence of major elements in rivers. *Treatise on Geochemistry* **5** (1), 207–223.
- Millot, R., Gaillardet, J. É., Bernard, D. & Allègre, C. J. 2003 Northern latitude chemical weathering rates: clues from the Mackenzie River Basin, Canada. *Geochimica et Cosmochimica Acta* **67** (7), 1305–1329.
- Mortatti, J. & Probst, J. L. 2003 Silicate rock weathering and atmospheric/soil CO₂ uptake in the Amazon Basin estimated from river water geochemistry: seasonal and spatial variations. *Chemical Geology* **197** (1–4), 177–196.
- Nazri, M. A. A., Tan, L. W., Kasmin, H., Syafalni, S. & Abustan, I. 2016 Geophysical and hydrochemical characteristics of groundwater at Kerian irrigation scheme. *IOP Conference Series: Materials Science and Engineering* **136** (1), 1–14.
- Pazi, I. 2008 Water mass properties and chemical characteristics in the Saros Gulf, Northeast Aegean Sea (eastern Mediterranean). *Journal of Marine Systems* **74** (1–2), 698–710.
- Piper, A. M. 1984 A graphic procedure in the geochemical interpretation of water-analyses. *Neurochemistry International* **6** (1), 27–39.
- Pu, T., He, Y. Q., Zhu, G. F., Zhang, W., Cao, W. H., Chang, L. & Wang, C. F. 2012 Geochemistry of surface and ground water in the Lijang Basin, Northwest Yunnan. *Environmental Science* **33** (1), 48–54.
- Qiao, B. J., Wang, J. B., Huang, L. & Zhu, L. P. 2017 Characteristics and seasonal variations in the hydrochemistry of the Tangra Yumco basin, central Tibetan Plateau, and responses to the Indian summer monsoon. *Environmental Earth Sciences* **76**, 162.
- Ramesh, R. P., Zhang, F., Faizan, U. R., Wang, G. X., Ye, M., Zeng, C. & Tang, H. D. 2018 Spatiotemporal variations of hydrogeochemistry and its controlling factors in the Gandaki River Basin, Central Himalaya Nepal. *Science of the Total Environment* **622–623**, 770–782.
- Ren, C. F. 2017 *Research on Optimal Promotion of Water Resources Carrying Capacity Under Uncertainty in Shiyang River Basin*. China Agricultural University, Beijing.
- Rodolfo, L. B., Nóbrega, A. C., Guzha, G. L., Ricardo, S. S., Amorim, E. G., Couto, H. J., Hughes, H. F., Jungkunst, G. G., Rlb, N., Guzha, A. C. & Lamparter, G. 2018 Impacts of land-use and land-cover change on stream hydrochemistry in the Cerrado and Amazon biomes. *Science of the Total Environment* **635**, 259–274.
- Saleh, A., Al-Ruwaih, F. & Shehata, M. 1999 Hydrogeochemical processes operating within the main aquifers of Kuwait. *Journal of Arid Environments* **42** (3), 195–209.
- Shi, P. J., Wang, Z. J. & Li, W. 2012 Urban spatial expansion process and pattern in Shiyang River Basin. *Scientia Geographica Sinica* **32** (7), 840–845.
- Tripathee, L., Kang, S., Huang, J., Sillanpää, M., Sharma, C. M., Lüthi, Z. L. & Paudyal, R. 2014 Ionic composition of wet precipitation over the southern slope of central Himalayas, Nepal. *Environmental Science and Pollution Research* **21** (4), 2677–2687.
- Trower, L. 2009 Spatial variations in chemical weathering and CO₂ consumption in Nepalese High Himalayan catchments during the monsoon season. *Geochimica et Cosmochimica Acta* **73** (21), 6692–6696.
- Wang, F. C., Wang, S. S., Li, T. D., Cai, X. J. & Zhao, L. 2011 Initial discussion on classification of granites and prospecting direction in Qilianshan area. *Acta Petrologica Sinica* **27** (12), 3823–3830.
- Wen, X. H., Wu, Y. Q., Chang, J., Su, J. P., Zhang, Y. H. & Liu, F. M. 2004 Analysis on the spatial differentiation characteristics of hydrochemistry in the Heihe River Watershed. *Arid Zone Research* **21** (1), 1–6.
- WHO 2011 *Guidelines for Drinking-Water Quality*. WHO Chronicle. World Health Organization, Geneva.
- Wilcox, L. V. 1948 *The Quality of Water for Irrigation Use*. United States Department of Agriculture, Economic Research Service, Washington, DC.
- Wu, L. N., Sun, C. J., He, Q., Chen, W. & Zhang, Y. Q. 2017 Analysis of temporal and spatial variation of hydrochemical characteristics of the typical Inland River in the Middle of Tianshan Mountains. *Research of Soil and Water Conservation* **24** (5), 149–156.
- Xiao, J. Y., Zhao, P. & Li, H. 2016 Spatial characteristic and controlling factors of surface water hydrochemistry in the Tarim River Basin. *Arid Land Research* **39** (1), 33–40.
- Yang, L., Zhu, G. F., Shi, P. J., Li, J. F., Liu, Y. F., Tong, H. L., Liang, F., Pan, H. X., Guo, H. W. & Zhang, Y. 2018 Spatiotemporal characteristics of hydrochemistry in Asian arid inland basin – a case study of Shiyang River Basin. *Environmental Science and Pollution Research* **3** (25), 2293–2302.
- Zhang, L. D. 2015 *Water Resources Management and Decision-Making Model Research for Irrigation District in Shiyang River Basin*. China Agricultural University, Beijing.
- Zhou, J. J., Shi, P. J. & Shi, W. 2012 Temporal and spatial characteristics of climate change and extreme dry and wet events in Shiyang River Basin from 1960 to 2009. *Journal of Natural Resources* **27** (1), 143–152.
- Zhu, G. F., Liu, Y. F., He, Y. Q., Pu, T., Li, J. F. & Yang, L. 2015 Variations of chemical features in a monsoon glacier watershed, southeastern Tibet Plateau. *Environmental Earth Sciences* **74** (7), 5793–5803.